When advanced models can lead to lower safety: Codified design of structures against wind loads

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ABSTRACT: In modern structural design standards, reliability requirements are verified following a semi-probabilistic approach, in which the safety of a structure is controlled by the selection of characteristic values and partial safety factors. These standards are typically based on simplified models of load and structural performance, whose parameters are selected conservatively, which leads to additional "hidden" safety. If these models are replaced by more advanced and potentially more accurate models, some of this hidden safety might be lost. This study investigates the hidden safety associated with the wind load model of the Eurocode. In particular, we estimate the hidden safeties included in the wind velocity pressure maps and the gust-, the pressure- and the roughness-coefficient. In order to make general statements, a generic portfolio representing the most common design situations is analyzed. The effect of advanced models (e.g. a "virtual wind tunnel") on these hidden safeties is considered. First, we estimate how the application of advanced modeling techniques influences the material usage and the reliability of structures. In a second step, we recalibrate the partial safety factor regarding wind, so that designs gained by advanced modeling techniques lead to the same avarage level of safety as designs following the Eurocode. With this recalibrated partial safety factor we reevaluate the effect on the material usage and the reliability.

1. INTRODUCTION

In modern structural design standards, such as the Eurocode, the reliability requirements are verified by a semi-probabilistic approach: Structural designs must fulfill the following inequality:

$$E_d = E_k \cdot \gamma_E \leq \frac{R_k}{\gamma_R} = R_d \qquad (1)$$

whereby E_k and R_k are the characteristic values, γ_E and γ_R are the partial safety factors and E_d and R_d are design values of the actions and the resistances. To ensure the structural safety, the partial safety factors are typically values greater than 1 and the characteristic values are usually lower quantile values on the resistance side and higher quantile values on the action side.

In addition to the two well known safety components, namely the choice of the partial safety factors and the characteristic values, there is a third, often overlooked, safety component: The hidden safety. To understand hidden safety, it is useful to investigate the Eurocode design approach (see figure 1): In this design approach one can identify four different models being used. The load model $\mathscr{M}_L$, the statc model $\mathscr{M}_S$, the material model $\mathscr{M}_M$ and the resistance model $\mathscr{M}_R$.

$$\begin{tikzcd}[row sep=small]
\text{Load model } \mathcal{M}_L \arrow[d] & & \text{Material model } \mathcal{M}_M \arrow[d] \\
\text{Characteristic load} \arrow[d] & & \text{Characteristic material} \arrow[d] \\
\text{Partial safety factor } \gamma_{\mathcal{M}_L} \arrow[d] & & \text{Partial safety factor } \gamma_{\mathcal{M}_M} \arrow[d] \\
\text{Static model} \arrow[d] & & \text{Resistance model} \arrow[d] \\
\text{Partial safety factor } \gamma_{\mathcal{M}_S} \arrow[d] & & \text{Partial safety factor } \gamma_{\mathcal{M}_R} \arrow[d] \\
\text{Design load effect} & \overset{!}{\geqslant} & \text{Design resistance}
\end{tikzcd}$$

Figure 1: Design approach of the Eurocode CEN (2002).

The characteristic values depend on the load model $\mathscr{M}_L$ and the material model $\mathscr{M}_M$, hence are functions of these models. Moreover, the design load effect and the design resistance are functions provided by the static model $\mathscr{M}_S$ and the resistance model $\mathscr{M}_R$. Considering this nesting of functions equation (1) can be reformulated as equation (2). In this formulation the effect of the models being used is explicitly included.

$$E_d = \mathscr{M}_S\left(E_k\left(\mathscr{M}_L\right) \cdot \gamma_{\mathscr{M}_L}\right)\right) \cdot \gamma_{\mathscr{M}_S} \qquad (2)$$
$$\leq \frac{\mathscr{M}_R\left(\frac{R_k(\mathscr{M}_M)}{\gamma_{\mathscr{M}_M}}\right)}{\gamma_{\mathscr{M}_R}} = R_d$$

Note that Eurocode 0 [CEN (2002)] distinguish between four partial safety factors $\gamma_{\mathscr{M}_L}$, $\gamma_{\mathscr{M}_S}$, $\gamma_{\mathscr{M}_M}$ and $\gamma_{\mathscr{M}_R}$. With this formulation the uncertainty of all four models being used could be treated separately. However, for the sake of simplicity, the Eurocode merges the partial safety factors on the action and the resistance side (see equation 3 - 4).

$$\gamma_E = \gamma_{\mathscr{M}_L} \times \gamma_{\mathscr{M}_S} \qquad (3)$$
$$\gamma_R = \gamma_{\mathscr{M}_M} \times \gamma_{\mathscr{M}_R} \qquad (4)$$

How can one now conclude, that a structure fulfilling inequality 2 leads to a design that does not fail? The answer is: One cannot ensure this, since models are not perfect representations of reality. However, one can do the best to ensure it for most cases, leading to an acceptable failure rate of our buildings. The semi probabilistic partial safety concept accomplishes this goal explicitly with the two – above already mentioned – safety components (partial safety factors and the characteristic values) and implicitly by hidden safety trough conservative load-, static-, material- and/or resistance-models. If these models are conservative the load effects are overestimated or rather the resistances are underestimated, leading to a larger design resistance. Investigation of hidden safety is not straightforward, since it is difficult to judge if a model is conservative or not. The reason for this is the following: A model is conservative, if the value calculated by this model lays on the safe side relative to the true value, hence is biased. This, however, is difficult to claim, since the true value is typically unknown.

The investigation of the hidden safety arising from a conservative model becomes important if one wants to replace this model by a more advanced and presumably more accurate model. This replacement impacts the safety of structures in two contradictory ways:

- More advanced models usually have less model uncertainty. This increases the probability that a structure that fulfills inequality (2) does not fail.
- The loss of conservativeness, namely the loss of the bias, leads to lower design resistance, which reduces the structural safety.

Depending on which of these effects dominates, the structural safety can increase or decrease. To preserve the same level of safety, the partial safety factor concept should react to this change. We show exemplarily how this could be done for the wind load model of Eurocode [CEN (2005)]. For this, we consider an exchange of the Eurocode wind load model $\mathscr{M}_{Wind,EC}$ with more advanced modeling techniques (e.g. a virtual wind tunnel) $\mathscr{M}_{Wind,adv}$ and study the effect on the structural safety and the material usage. In a second step we introduce an additional partial safety factor for wind of the Eurocode, so that the same level of safety is achieved, if $\mathscr{M}_{Wind,EC}$ or $\mathscr{M}_{Wind,adv}$ is used. With the recalibrated partial safety factor we again study the effect on the material usage. To draw general conclusions we use a portfolio of idealized but representative design situations for steel structures. Prior to the investigation of hidden safety we shortly summarize the Eurocode wind load model.

2. THE WIND LOAD MODEL OF THE EUROCODE

The wind load model of the Eurocode is based on the wind load chain of Davenport [Davenport (1961),Davenport (1983)]. It consists of five fundamental aspects: The wind climate, the terrain, the aerodynamic response the mechanical response and the design criteria.

Following the wind load chain, the Eurocode defines the characteristic wind load q_k as:

$$q_k = q_{b,k} \cdot c_{e,k} \cdot c_{f,k} \cdot c_{s,k} \cdot c_{d,k} \tag{5}$$

The different coefficients are characteristic values (indexed with k):

- $q_{b,k}$ Wind velocity pressure: Defined as the 10 minute mean velocity pressure at a height of 10 [m] above ground with a roughness length of 0.05 [m] and a return period of 50 years.
- $c_{e,k}$ exposure coefficient: Considers the roughness of the terrain and the height of the structure. It is based on empirically determined formulas. Eurocode assumes that these formulas are estimators of the expected exposure coefficient and thus the characteristic value is the mean.
- $c_{f,k}$ force coefficient: Addresses the geometry of the structure. Historically its values are based on investigations of Cook (1985) and obtained as the 78 [%] quantile of the – assumed to be Gumbel distributed – yearly maxima of the pressure coefficient.
- $c_{sd,k} := c_{s,k} \cdot c_{d,k}$ structural factor: Accounts for the fact that wind peak pressures do not occur simultaneously on the total surface of the structure (represented trough c_s) as well as the dynamical effect caused by wind turbulences exiting the structure in its eigenfrequencies (represented trough c_d). Eurocode assumes that these formulas are estimators of the expected structural factor and thus the characteristic value is the mean.

Table 1 summarizes how Eurocode defines the characteristic values from the respective underlying distributions.

Table 1: Characteristic values of the wind load model components.

$$q_{b,k} = F_{Q_b}^{-1}(0.98)$$
$$c_{e,k} = \mathrm{E}[C_e]$$
$$c_{f,k} = F_{C_f}^{-1}(0.78)$$
$$c_{sd,k} = \mathrm{E}[C_{sd}]$$

In the following the four wind load model components ($q_{b,k}$, $c_{e,k}$, $c_{f,k}$ and $c_{sd,k}$) are modeled probabilistically. Following Vrouwenvelder (1997) and Köhler et al. (2017) we define the standardized distributions of the respective wind load model components as in Table 2. These distributions are assumed to be the "true" distributions, meaning that they only contain aleatoric uncertainties and do not reflect epistemic uncertainties.[1]

Table 2: Standardized distributions of wind load model components.

	Mean	c. o. v.
$Q_b \sim \mathscr{G}$	1	0,25
$C_e \sim \mathscr{LN}$	1	0,15
$C_f \sim \mathscr{G}$	1	0,1
$C_{sd} \sim \mathscr{LN}$	1	0,1

3. HIDDEN SAFETY IN THE EUROCODE WIND LOAD MODEL

The characteristic values in the Eurocode are only estimates of the characteristic values of the true distribution. This estimation, however, is conservative, meaning that it overestimates the characteristic values in most chases. Figure 2 illustrates the situation exemplarily for the wind velocity pressure q_b

[1] The subdivision into epistemic and aleatoric uncertainty and the definition the true distribution is a simplified way of thinking. However, in this context it is helpful for comprehension. A philosophically well-founded framework can be found in [Cartwright and McMullin (1984),Cartwright (1994),Cartwright et al. (1994),Bailer-Jones (2009)].

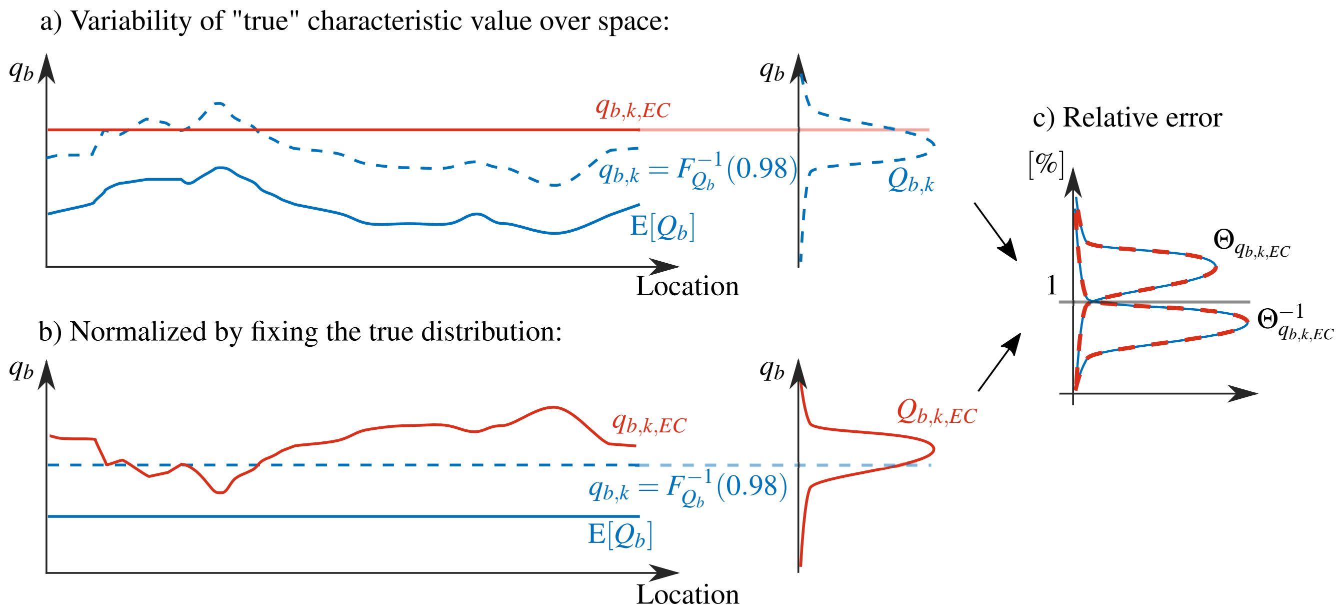

Figure 2: Relationship between the characteristic value of the true distribution $q_{b,k}$ and the characteristic value according to Eurocode q_{b,k_EC} and the derivation of the relative error $\theta_{q_{b,k,EC}}$.

and the subsequent derivation of the relative error in two different equivalent perspectives: Once with fixed characteristic value of the Eurocode $q_{b,k,EC}$ and once with fixed true characteristic value $q_{b,k}$. Both perspectives lead to the same results.

To describe the the error in the estimation of the characteristic values we define a relative error of the characteristic values according to $\mathscr{M}_{Wind,EC}$ relative to the characteristic value of the true distribution:

$$\Theta_{q_{b,k,EC}} = \frac{Q_{b,k,EC}}{Q_{b,k}} \tag{6}$$

In literature, typically the inverse of this error $\Theta^{-1}_{q_{b,k,EC}} = \frac{Q_{b,k}}{Q_{b,k,EC}}$ is specified. Table 3 summarizes the distributions of this relative error regarding each component of the wind load model. The choice is based on Davenport (1989), Vrouwenvelder (1997) and the evaluation of the wind data of 265 meteorological stations of the German Meteorological Service [DWD (2018)]. The detailed derivation of the model errors of this study can not be described in detail, due to lack of space.

Table 3: Relative errors $\frac{\text{True char. value}}{\text{Char. value of EC}}$.

	Mean	c.o.v.
$\Theta^{-1}_{q_{b,k,EC}} \sim \mathscr{LN}$	0.8	0.30
$\Theta^{-1}_{c_{e,k,EC}} \sim \mathscr{LN}$	0.8	0.15
$\Theta^{-1}_{c_{f,k,EC}} \sim \mathscr{LN}$	0.9	0.20
$\Theta^{-1}_{c_{sd,k,EC}} \sim \mathscr{LN}$	1.0	0.15

4. ADVANCED WIND LOAD MODEL

If advances wind load modeling techniques are applied the relative error in the estimation of the characteristic values changes. Table 4 summarizes the utilized distributions. The choice is based on Long (2004), Kelly and Jørgensen (2017), Sørensen et al. (2012), Ellingwood and Tekie (1999), Dora and Frank (2000), Cóstola et al. (2008), ISO and OIML (2008) and the data of the the German Meteorological Service. Overall, there is only limited literature and data available to derive the model errors and some expert judgment had to be utilized.

Table 4: Relative errors $\frac{\text{True char. value}}{\text{Char. value of Adv}}$.

	Mean	c.o.v.
$\Theta^{-1}_{q_{b,k,adv}} \sim \mathscr{LN}$	1.0	0.10
$\Theta^{-1}_{c_{e,k,adv}} \sim \mathscr{LN}$	1.0	0.05
$\Theta^{-1}_{c_{f,k,adv}} \sim \mathscr{LN}$	1.0	0.15
$\Theta^{-1}_{c_{sd,k,adv}} \sim \mathscr{LN}$	1.0	0.10

Figure 3 exemplary plots the situation for the wind velocity pressure and the respective relative errors with fixed true characteristic value (as in Figure 2 b)).

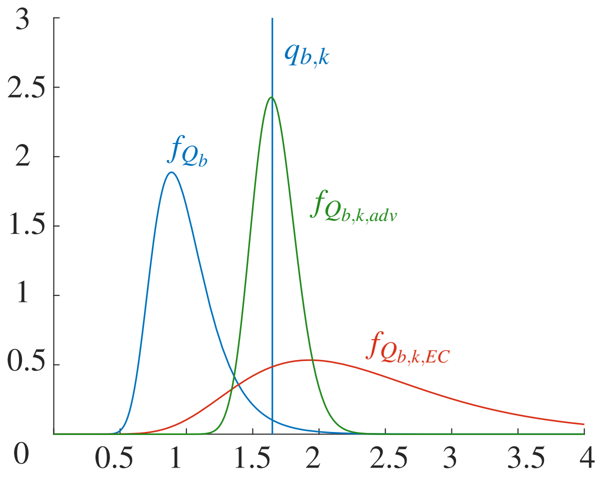

Figure 3: PDF and characteristic value of the wind velocity pressure (blue) and the PDF of the characteristic wind velocity pressure given in the Eurocode (red) and the advanced model (green).

5. DEFINITION OF A PORTFOLIO OF TYPICAL DESIGN SITUATIONS OF STEEL STRUCTURES

To draw general conclusions we apply the distributions of the relative errors of $\mathscr{M}_{Wind,EC}$ and $\mathscr{M}_{Wind,adv}$ to a representative portfolio of design situations of steel structures. The portfolio is defined via the following generic limit state function g. This limit state function is also utilized in the ongoing revision of the Eurocode [Köhler et al. (2017)].

$$g = p \cdot \Theta_R \cdot R - (1-a_Q) \cdot [a_G \cdot G_S + (1-a_G) \cdot G_P] - a_Q \cdot Q \tag{7}$$

where

- Q: wind load.
- R: Steel yielding strength.
- Θ_R: Resistance model uncertainty.
- G_S: Self-weight of steel structures.
- G_P: Permanent load.
- a_Q: Parameter representing different proportions between wind load and self-weight. Ten equally spaced and equally weighted values in the range $[0.2; 0.8]$ are considered.
- a_G: Parameter representing different proportions between permanent load and self-weight. Three equally spaced and equally weighted values in the range $[0.6; 1.0]$ are considered.
- p: Design variable (e.g. cross section dimensions) defined via equation "*6.10*" of Eurocode 0 [CEN (2002)] as:

$$p = \frac{\gamma_M}{\theta_{R,k} \cdot r_k} \cdot [(1-a_Q) \cdot (a_G \cdot \gamma_S \cdot g_{S,k} + (1-a_G) \cdot \gamma_P \cdot g_{P,k}) + a_Q \cdot \gamma_Q \cdot q_k] \tag{8}$$

The characteristic values are defined as:

$$\theta_{R,k} = \mathrm{E}[\Theta_{R,k}] \tag{9}$$

$$r,k = \mathrm{E}[R] - 2 \cdot \sqrt{\mathrm{Var}[R]} \tag{10}$$

$$g_{S,k} = F_{G_S}^{-1}(0.5) \tag{11}$$

$$g_{P,k} = F_{P_S}^{-1}(0.5) \tag{12}$$

$$q_k = F_{Q_b}^{-1}(0.98) \cdot \mathrm{E}[C_e] \cdot F_{C_f}^{-1}(0.78) \cdot \mathrm{E}[C_{sd}] \tag{13}$$

Moreover, $\gamma_Q = 1.5$, $\gamma_M = 1.0$ and $\gamma_S = \gamma_P = 1.35$ are the partial safety factors of the Eurocode regarding wind load, steel yield strength, permanent loads and self-weight.

Table 5 shows the utilized distributions.

Table 5: Standardized stochastic models based on Vrouwenvelder (1997) and Köhler et al. (2017).

	Mean	c.o.v.
$\Theta_R \sim \mathscr{LN}$	1	0.05
$R \sim \mathscr{LN}$	1	0.07
$G_S \sim \mathscr{N}$	1	0.04
$G_P \sim \mathscr{N}$	1	0.10
Q	see above	

6. RESULTS

6.1. EFFECT ON THE MATERIAL USAGE

Based on the distributions of the characteristic values, we derive the distribution of the characteristic wind load $Q_{k,EC}$ and $Q_{k,adv}$ via equation (5). Note that this is not the distribution of the wind load, but of the characteristic value of the wind load. We utilize equation (8) to derive the distribution of the design variables P_{EC} and P_{adv} and calculate the distribution of the ratio $\frac{P_{adv}}{P_{EC}} \sim \mathscr{L}\mathscr{N}$ with $\mathrm{E}[\frac{P_{adv}}{P_{EC}}] = 0.60$ and $\mathrm{c.o.v.}[\frac{P_{adv}}{P_{EC}}] = 0.57$. Figure 4 plots the PDF of this ratio.

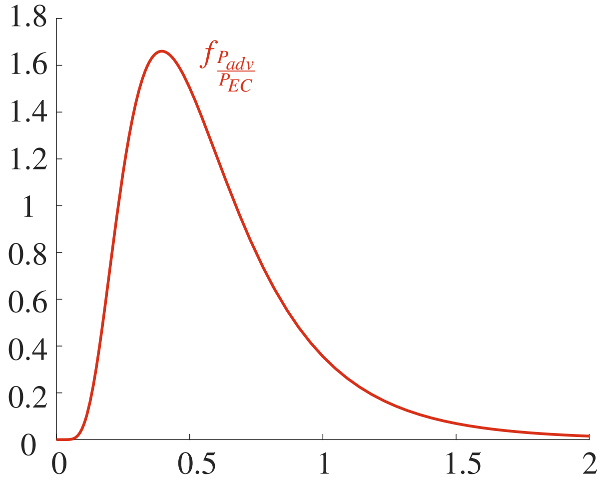

Figure 4: PDF of the ratio of the design variables according to a Eurocode design to those following an advanced design $\frac{P_{adv}}{P_{EC}}$.

The design variables represent the amount of resistance according to a Eurocode design or rather an advanced design. Assuming a one-to-one relationship of the resistance and the material effort, one can deduce that $\mathscr{M}_{Wind,adv}$ reduces the material usage by 40 [%] on average.

6.2. EFFECT ON THE RELIABILITY

In the next step, we investigate the effect on the reliability. For each design situation of the utilized portfolio the probability of failure $\Pr(F) = \Pr(g < 0)$ is calculated for both, the design utilizing $\mathscr{M}_{Wind,EC}$ or $\mathscr{M}_{Wind,adv}$, according to the following equations:

$$\Pr(F \mid \text{Design following } \mathscr{M}_{Wind,EC}) = \int_{\Omega_{R_{i,k}}} \Pr(F \mid R_{i,k,EC} = r_{i,k,EC}) \cdot f_{R_{i,k,EC}}(r_{i,k,EC})\, dr_{i,k,EC} \tag{14}$$

$$\Pr(F \mid \text{Design following } \mathscr{M}_{Wind,adv}) = \int_{\Omega_{R_{i,k}}} \Pr(F \mid R_{i,k,adv} = r_{i,k,adv}) \cdot f_{R_{i,k,adv}}(r_{i,k,adv})\, dr_{i,k,adv} \tag{15}$$

Notice that the design variable p is calculated with $R_{i,k,EC}$ or $R_{i,k,adv}$. Hence, the design follows the two different modeling approaches. However the wind load in the subsequent reliability analysis of the two different designs – Q in equation (7) – is the true wind load distribution: $Q = Q_b \cdot C_e \cdot C_f \cdot C_{sd}$.

Figure 5 boxplots the resulting annual reliability indices $\beta = -\Phi^{-1}(\Pr(F))$ of the portfolio of design situations for the two different design approaches.

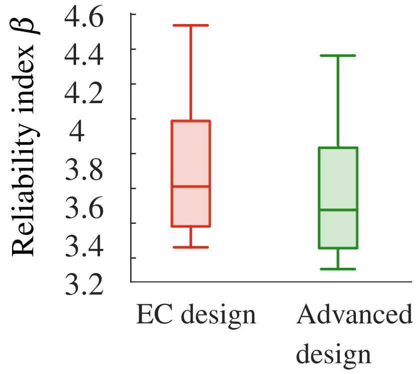

Figure 5: Boxplots of the annual reliability indices of the design situations of the considered portfolio of steel structures according to an design utilizing $\mathscr{M}_{Wind,EC}$ (red) or $\mathscr{M}_{Wind,adv}$ (green).

Assuming that each design situation of the portfolio is equally representative, the average reliabilities are $\mathrm{E}[\beta_{\mathscr{M}_{Wind,EC}}] = 3.72$ and $E[\beta_{\mathscr{M}_{Wind,adv}}] = 3.58$. Hence the reliability on average decreases if $\mathscr{M}_{Wind,EC}$ gets replaced through $\mathscr{M}_{Wind,adv}$.

6.3. *ADJUSTMENT OF THE PARTIAL SAFETY CONCEPT AND ITS EFFECT ON THE MATERIAL USAGE AND THE RELIABILITY*

To compensate the decrease of safety the partial safety concept should be adapted. Therefore we define a partial safety factor $\gamma_{Q,add}$ additional to the already existing partial safety factor of the Eurocode $\gamma_Q = 1.5$. Following Köhler et al. (2017) $\gamma_{Q,add}$ is found by minimizing the quadratic divergence of the average reliability index obtained from $\mathscr{M}_{\text{Wind},EC}$ to the reliability indices obtained from $\mathscr{M}_{\text{Wind},adv}$ for each design situation of the considered portfolio. This results in $\gamma_{Q,add} = 1.06$.

Therefore, if the coefficients of the wind load model are derived by advanced wind load modeling techniques $\mathscr{M}_{\text{Wind},adv}$, the design should be done with an partial safety factor of $\gamma_Q \cdot \gamma_{Q,add} = 1.5 \cdot 1.06 = 1.59$. Redoing the analysis with this new partial safety factor we get an average reliability index of $\text{E}[\beta_{\mathscr{M}_{\text{Wind},adv,\text{with }\gamma_{Q,adv}}}] = 3.69$. Note that this does not coincide with $\text{E}[\beta_{\mathscr{M}_{\text{Wind},EC}}] = 3.72$, since we did not align the average reliability index, but minimized the quadratic error.

Figure 6 illustrates how the recalibration of the partial safety factor preserves the safety level.

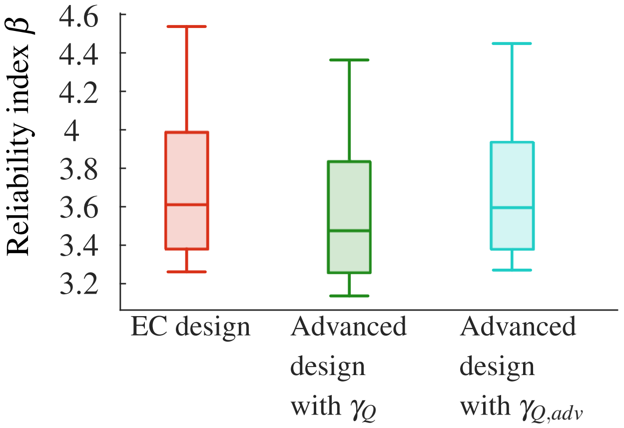

Figure 6: Boxplots of the annual reliability indices of the design situations of the considered portfolio of steel structures according to an design utilizing $\mathscr{M}_{\text{Wind},EC}$ (red), $\mathscr{M}_{\text{Wind},adv}$ with the old partial safety γ_Q factor (green) or $\mathscr{M}_{\text{Wind},adv}$ with the adapted partial safety factor $\gamma_{Q,add}$ (teal).

Obviously the increase of the partial safety factor leads to an increase in the material usage, but how much of the material usage reduction gained by $\mathscr{M}_{\text{Wind},adv}$ is maintained? Repeating the steps of section 6.1 with the additional partial safety factor and we find the distribution of the ratio $\frac{P_{adv,\text{with }\gamma_{Q,adv}}}{P_{EC}} \sim \mathscr{LN}$ with $\text{E}[\frac{P_{adv,\text{with }\gamma_{Q,adv}}}{P_{EC}}] = 0.64$ and $\text{c.o.v.}[\frac{P_{adv,\text{with }\gamma_{Q,adv}}}{P_{EC}}] = 0.57$. Figure 7 compares the PDF of this ratio with PDF of the previous ratio $\frac{P_{adv,}}{P_{EC}}$.

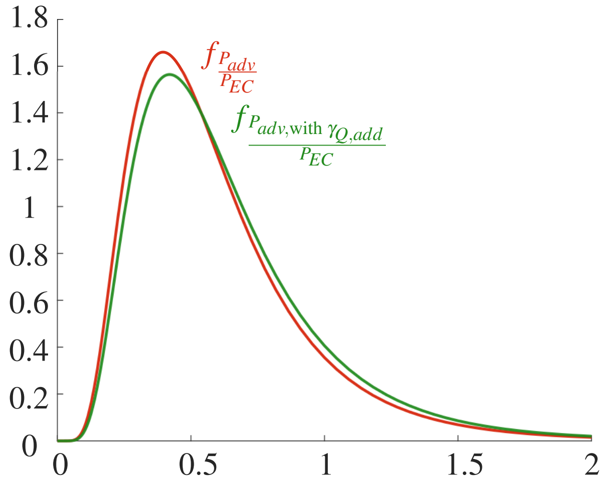

Figure 7: PDF of the ratio of the design variable according to an Eurocode design to the design variable of an advanced design $\frac{P_{adv}}{P_{EC}}$ or rather to the design variable of an advanced design with recalibrated partial safety factor $\frac{P_{adv,\text{with }\gamma_{Q,adv}}}{P_{EC}}$.

With the additional partial safety factor the average material usage is still reduced by 36 [%], relative to $\mathscr{M}_{\text{Wind},EC}$.

7. CONCLUSION

In this paper we studied the effect of replacing the standard Eurocode wind load model with more advanced – state of the art – wind load modeling techniques. In particular, we investigated the effect to the structural safety and the material usage in a portfolio of typical design situations of steel structures. We found that the average reliability index and Simultaneously the average material usage decrease significantly. In a second step we introduced an additional partial safety factor $\gamma_{Q,add}$. If advanced modeling techniques are applied the partial safety factor for Wind of 1.5 should be increased by this additional factor. This maintains the level of safety compared to a design done by the standard Eurocode model. Compared to the design gained by the standard Eurocode model the average material usage is still reduced substantially. It is very important to exploit this material saving potential, especially with regard to sustainability, since the building sector is one of the main material consumers [UN-environment (2017)].

With the given model assumptions, the study has shown that the application of advanced wind load modeling techniques can reduce the safety. The increase of safety gained by more advanced and more realistic wind load models with less model uncertainty could not compensate the loss of hidden safety due to conservative assumptions in the Eurocode model. In case of other models, this effect might be even stronger. Therefore, it is essential to investigate the effect to the safety if new modeling techniques are applied and to adapt the safety concept accordingly. This adaptation can only be carried out by means of a representative building portfolio and not for individual buildings.

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